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REVIEW

Recent Advances in the Design and Application of Shoulder Arthroplasty Implant Systems and Their Impact on Clinical Outcomes: A Comprehensive Review

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Purpose of Review: This narrative review comprehensively aims to analyze recent advancements in shoulder arthroplasty, focusing on implant systems and their impact on patient outcomes. The purpose is to provide a nuanced understanding of the evolving landscape in shoulder arthroplasty, incorporating scientific, regulatory, and ethical dimensions.

Recent Findings: The review synthesizes recent literature on stemless implants, augmented glenoid components, inlay vs onlay configurations, convertible stems, and associated complications. Notable findings include improved patient-reported outcomes with stemless implants, variations in outcomes between inlay and onlay configurations, and the potential advantages of convertible stems. Additionally, the regulatory landscape, particularly the FDA's 510(k) pathway, is explored alongside ethical considerations, emphasizing the need for standardized international regulations.

Summary: Recent innovations in shoulder arthroplasty showcase promising advancements, with stemless implants demonstrating improved patient outcomes. The review underscores the necessity for ongoing research to address unresolved aspects and highlights the importance of a standardized regulatory framework to ensure patient safety globally. The synthesis of recent findings contributes to a comprehensive understanding of the current state of shoulder arthroplasty, guiding future research and clinical practices.

Keywords: shoulder arthroplasty, rTSA, stemless implants, glenoid components, patient outcomes, innovations in arthroplasty

Introduction

Shoulder arthroplasty has evolved significantly over the last century, accompanied by a surge in novel applications and implant system development. Beginning in 1893, Dr. Jules Emile Péan implanted a metal shoulder prosthesis in Jules Perdoux, inspired by Dr. Themistocles Gluck's prior use of an ivory knee prosthesis.[1,2] Dr. Charles Neer's upper extremity work in 1955 demonstrated pain relief post-prosthesis in Neer 1 fractures and subsequent studies in 1974 laid the foundation for the modern Total shoulder arthroplasty (TSA).[3,4] Since then, TSA has demonstrated promising clinical outcomes, radiographic stability, low complication rates, and impressive implant longevity.[5,6]

In 1985, Dr. Paul Grammont introduced Reverse Total Shoulder Arthroplasty (RSA), offering an alternative to anatomic TSA while addressing high dislocation rates and glenoid support issues.[4,7–9] In 1998, the first RSA was performed in the United States and eventually received United States Food and Drug Administration (FDA) approval in 2003.[10] Current indications for RSA include arthritis, cuff tear arthropathy, proximal humerus fractures, tumors, and bone loss; this procedure has since demonstrated high success rates with ten-year survivorship as high as 94%.[11] From 2011 to 2017 the number of primary shoulder arthroplasties increased by 104%, and from 2017–2025 it is projected to further rise

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by 67–235% which will outpace the rates seen in Total Hip Arthroplasty and Total Knee Arthroplasty.[12] Further, there has been a substantial increase in RSA prevalence in the United States, in 2016 RSA contributed to only 55% of all shoulder arthroplasty cases, but by 2020 RSA increased to 70% of arthroplasty cases.[11,13–18] Traditionally shoulder arthroplasty was done in younger patients. As indications have evolved, the patient cohort has as well and TSA and HA can be completed in patients under 65 for osteoarthritis, and implant survivorship is generally favorable with 10-year survivorship rates above 80% for HA and TSA.[19] While still controversial, new research has begun to highlight the use of RSA in younger patients. While RSA was traditionally performed in patients over 70 due to concerns surrounding implant wear in patients under 70 indications has evolved in the under 70 age group to younger patients with osteoarthritis, and failed total shoulder arthroplasty and has been studied in patients as young as 55.[20–22]

Continued advancements, fueled by cadaveric studies exploring glenohumeral joint anatomy and protective attachments, have led to the development of modular implant systems better matching the native shoulder.[23–26] Specifically, innovation in humeral head component design include transitions from lengthy, limited and non-anatomic prostheses to the more modern designs, which are shorter or stemless and emphasize bone preservation.[26] In addition, the evolution of glenoid components includes the development and utilization of polyethylene-based, uncemented metal-backed, and hybrid implants.[27] These advancements aim to preserve bone stock and enhance shoulder function while addressing complex pathologies, enhance precision and optimize patient outcomes.[27] With data predictors indicating that shoulder arthroplasty will soon surpassing rates of other major joint procedures, understanding the rapidly evolving implant systems and design becomes paramount.[12,28,29] Therefore, the purpose of this review is to provide a comprehensive overview of the recent advances in the design and application of shoulder arthroplasty implant systems, exploring benefits, drawbacks, and relevant regulatory and ethical considerations.

Material and Methods

Literature Review Strategy

The present study represents a comprehensive narrative review of the scientific literature related to shoulder arthroplasty, focusing on recent advancements in implant systems. Electronic databases, including EMBASE, MEDLINE, PubMed and Scopus, were meticulously searched for relevant studies published from database inception to January 1, 2024. The search terms encompassed variations of "shoulder arthroplasty", "implant systems", "stemless implants", "augmented glenoid components", "inlay vs onlay configurations", "convertible stems", and "complications in shoulder arthroplasty". The inclusion criteria were the following: 1) peer-reviewed articles, systematic reviews, meta-analyses, and clinical trials reporting on advancements in shoulder arthroplasty implant systems, and 2) published in English, with 3) full-text available.

Data Extraction and Synthesis

Pertinent studies were identified, sorted, and screened by two independent reviewers with a third reviewer available for any necessary arbitration. Upon identifying studies that met the inclusion criteria, the reviewers conducted a rigorous data extraction process. Key outcome measures, including patient-reported outcomes, range of motion, and complications associated with different implant systems, were systematically extracted. The findings from each study were meticulously synthesized to construct a coherent narrative review that delineates the significant advancements, comparative analyses, and unresolved aspects within the domain of shoulder arthroplasty. This methodical approach aimed to present a comprehensive and scientifically grounded overview of recent innovations.

Regulatory and Ethical Analysis

Incorporated within the methodology is a qualitative analysis of the regulatory and ethical considerations surrounding shoulder arthroplasty. The evolving FDA framework, with a focus on the 510(k) pathway, was scrutinized to comprehend the ethical implications associated with device clearance. This analysis was complemented by a review of international perspectives, emphasizing the need for a standardized regulatory framework. The inclusion of these components in the methodology ensures a holistic exploration of recent innovations within the broader context of regulatory and ethical dimensions.

Results

Historical Perspective

The first-generation humeral implants, designed by Neer in 1951, featured a mono-block design with a single humeral head size and three stem sizes. These implants were originally developed to treat proximal humerus fractures.[3] In 1973, Neer updated this design to include two humeral head sizes and a polyethylene glenoid component, expanding its application to patients with glenohumeral arthritis.[30] The second-generation of humeral implants, introduced in the 1990s, adopted a modular design, compromising a separate humeral head and stem connected by a Morse taper system.[31] The modularity of these implants was expected to facilitate selection of the best head size for the patient's anatomy. As additional anatomical studies of the humerus were conducted, future designs aimed to adapt the prosthesis to the patient's anatomy. With this concept in the mind, the third generation of humeral implants was introduced in the 1990s. This implant featured the ability to modify multiple properties including, inclination, retroversion, offset, and humeral head and stem diameters.[18,32] While updates in humeral implant design were anticipated to improve patient outcomes, many studies have indicated that although newer designs may improve ease of surgery, they do not necessarily result in better patient outcomes.[33–35]

As a direct result of poor outcomes observed in patients with rotator cuff arthropathy undergoing anatomic TSA, Dr. Neer introduced RSA in 1974. However, early designs yielded unsatisfactory results, including problems like glenoid loosening and implant breakage.[32,36] The foundation for current RSA implants was established in 1985 by Paul Grammont, whose design emphasized an implant with a medial and distal center of rotation and an increased deltoid moment arm to compensate for rotator cuff injury and lack of function.[36,37] However, this design came with new concerns such as scapular notching and inherent loss of external rotation. For example, in a retrospective study of 461 shoulders that received Grammont-type RSA, 68% of cases were reported to have scapular notching.[38] Subsequently, newer designs of the RSA system have attempted to modify various aspects of the implant to address scapular notching and loss of external rotation.[36,39]

Humeral Component

Fixation and Design

The fixation and design of the humeral component in Total Shoulder Arthroplasty (TSA) play a critical role in ensuring the success and longevity of the procedure. The humeral component, which replaces the damaged or arthritic head of the humerus, requires secure fixation within the bone to withstand the biomechanical forces of the shoulder joint. The design considerations include selecting an appropriate humeral head size, optimizing the articulation with the glenoid component, and ensuring proper alignment to restore the natural biomechanics of the shoulder. The fixation methods may involve cemented or press-fit techniques, with the goal of achieving stable implant fixation and promoting early functional recovery. Additionally, the humeral component design aims to provide sufficient range of motion, reduce the risk of complications, and enhance overall shoulder function.

Stemmed vs Short-Stem or Stemless

Since Neer's original mono-block design, humeral implants have evolved significantly. Initial designs were stemmed, set to occupy approximately the proximal third to half of the humerus. While well-fitted stems facilitated good alignment and stability, they were associated with metaphyseal stress shielding, periprosthetic fractures, and complicated revisions.[40]

Short-stem implants were designed to compress the cancellous bone of the proximal metaphysis with the advantage of preserving bone stock and reducing risk of stress shielding and periprosthetic fractures.[41] However, concerns have been raised regarding potential malalignment and adverse bone reactions associated with short-stem implants. Short stems that fail to engage the cylindrical portion of the endosteal canal can potentially become misaligned and alter humeral head positioning.[26] To enhance stability of short stems, implants can be designed with larger diameters. However, this approach carries the risk of stress shielding and, in extreme cases, bone resorption.[33,40,42,43] Therefore, it is important to be mindful of canal fill ratio when designing short- stem implants to prevent stress shielding of the metaphysis.

One of the earliest attempts at a stemless design was the resurfacing implant in the late 1970s. Resurfacing involves covering the native head of the humerus with a metal cap to preserve the bone. This design requires minimal bone

resection making it advantageous in patients with significant proximal humerus deformity. Additionally, it reduces the risk of periprosthetic fractures and facilitates easier revision if needed. However, achieving stability in patients with inadequate bone stock proves challenging with this procedure, and maintaining the native humeral head makes it difficult to obtain appropriate exposure to accurately implant the glenoid component.[33] As a result, the utilization of this procedure has declined. To preserve bone stock while addressing the challenges of the resurfacing approach, stemless designs with metaphyseal fixation were introduced in 2004. Additional benefits include avoidance of stress shielding, easier revision, and humeral head positioning independent of shaft position.[44] Making it a beneficial option for patients with deformity or difficult anatomy.

Short-stem and stemless implants are also used in RSA, offering similar advantages to those utilized in TSA, such as preservation of bone, reduced risk of periprosthetic fractures, and easier revision. However, a disadvantage of stemless implants in both TSA and RSA is that they require good bone quality, making them less suitable for elderly patients and those with osteoporotic bone.[41] A meta-analysis conducted by Shin et al included 122 subjects with stemless implants and 122 patients with stemmed implants. They reported that while postoperative constant scores (Mean difference, (MD):2.07, p=0.42) and complication rates (Odds ratio (OR) 1.22, p=0.68) did not significantly differ between stemmed and stemless shoulder arthroplasty, stemless implants demonstrated better forward elevation (MD:9.39, p=0.04) and external rotation (MD:4.63, p=0.04) post-operation.[41] However, the study was unable to determine if there was a significant difference in pre-operative range of motion as well, which could contribute to the difference found post-operatively. In contrast, Dasari et al[12] found no significant difference in forward flexion (MD=0,24, p=0.92) or external rotation (MD=3.31, p=0.05) between stemmed and stemless implants in their meta-analysis of 5 clinical studies with a total of 584 patients. Additionally, Rasmussen et al found no difference in short-term survival rates among 761 patients treated with a stemless implant and 4398 patients treated with a stemmed implant (0.953 vs 0.958, p=0.77). Additional long-term evaluation and randomized controlled trials investigating stemless versus stemmed implants need to be performed to determine whether stemless designs are superior to conventional designs in both TSA and RSA.

Studies assessing stemless implants, such as Krukenberg et al retrospective review demonstrated significant advancements among patients undergoing HA or TSA with these implants.[45] At the 2-year follow-up, substantial improvements were observed in the Constant Murley Score (CMS) from 26 to 70 ($p < 0.001$), Subjective Shoulder Value (SSV) from 34% to 84% ($p < 0.001$), and American Shoulder and Elbow Surgeons (ASES) score from 34 to 86 ($p < 0.001$).[44] Notably, the TSA group in the study exhibited superior patient-reported outcomes (PROs) when compared to HA in ASES (90.6 vs 74.6; $p < 0.001$), CS (74.7 vs 59; $p < 0.001$), and SSV (87.1 vs 75.2; $p = 0.0018$). Gallacher's evaluation of stemless components in TSA indicated an Oxford Shoulder Score (OSS) of 38 at the 2-year follow-up, other studies corroborated a similar OSS at 42.0.[46,47] Additionally, Smith et al showcased a Kaplan Meier survivorship score of 98.7% at 12 months, underscoring the durability of these stemless implants.[47] The comparisons between stemless and stemmed implants play a pivotal role in evaluating the viability of stemless models. No significant differences were noted in mean ASES, SANE, or CS between these implants. Additionally range of motion (ROM) measurements displayed a forward elevation (FE) of 157° and external rotation (ER) of 29° in the stemless group, contrasted with 157° of FE and 59° of ER in the stemmed group.[48] Further studies by Goldberg and Ushock echoed similar ROM and CS outcomes for stemless TSA, with Goldberg reporting a final Visual Analog Scale (VAS) for pain at 0.4 showing that ROM is similar between stemless and stemmed, and pain is well controlled with stemless TSA[49,50] (Table 1).

Table 1 Stemmed vs Stemless Component Overview

	Benefits	**Negatives**
Stemmed	Good alignment, and stability.	Associated with complicated revisions, metaphyseal stress shielding, and periprosthetic fractures.
Short stem/ Stemless	Preserves bone stock, and reduces the risk of stress shielding	Increases potential for malalignment, and adverse bone reactions.

Convertible Platform Stems

Another stem option is the convertible platform stem, allowing for conversion to RSA from TSA without stem removal. The advantages of this design include reduced operative time, blood loss, and complications, as the initial stem placement is maintained.[12] Crosby et al evaluated convertible stems and demonstrated no significant difference between the exchange group and retention group in ASES (30 vs 39 degrees, p = 0.073), CS (21 vs 25 degrees, p = 0.051), or IR (p = 0.163).[51] However, the retention group exhibited a higher postoperative range of motion in external rotation (ER) (11 vs 26 degrees, p = 0.006), and forward flexion (FF) (96 vs 112, p = 0.055). However, the benefits of this system are contingent on an accurately implanted component during the initial surgery. If poorly positioned, the stem may still necessitate removal at revision, thus negating the potential advantages of the system.[52]

Cemented vs Cementless

Traditionally, cement fixation of the humeral implant has been considered the standard. Cemented stems are favored in patients with poor bone quality, as cement can fill in a bone/prosthesis mismatch. Additionally, if there is concern for infection, cement can act as a carrier for antibiotics.[53] However, disadvantages of cement fixation include increased operative time and cost as well as difficult revisions. Consequently, cementless fixation has become a popular option over the past two decades. Early reports investigating cementless or press-fit implants with the Neer prosthesis demonstrated long-term results that were significant for radiographic changes concerning for loosening.[54,55] Torchia et al reported that 49% of their press-fit components had loosened compared to none of the cemented humeral components, concluding that cement fixation was preferable to press-fit.[56]

While early designs of cementless implants featured a smooth, press-fit fixation, newer models began incorporating bony ingrowth surfaces to provide biologic fixation. Initial designs consisted of porous coating isolated to the humeral head. Early reports of mid-term results found loosening rates of approximately 10%.[57] In 1995, the original design was updated to a circumferential porous coating, covering the proximal ¼ of the humerus. In their review of this design on 76 shoulders, Throckmorton et al reported improvements in clinical outcomes, a low incidence of radiolucent lines (6.58%), and no humeral loosening at a mean follow-up of 4.3 years.[58] This led their institution to only use cemented implants when substantial bone loss prevented them from using an ingrowth implant. In a randomized controlled trial of 80 cemented fixations and 81 uncemented fixations conducted by Litchfield et al, they found that the cemented group had significantly higher Western Ontario Arthritis of the Shoulder Index (WOOS) scores at 12 (MD=8.9, p=0.009), 18 (MD=13.1, p=0.001), and 24 (MD=8.6, p=0.028) months.[59] Additionally, the cemented group demonstrated better strength (MD=3, p=0.036) and forward flexion (MD=12, p=0.047) at 12 months, but no significant difference was seen at 24 months. Therefore, they concluded that cemented fixation is better for achieving optimal quality of life, range of motion, and strength. Notably, the implant used was not specifically designed for bony ingrowth; however, it was commonly inserted with a cementless fixation. More recent studies have concluded that press-fit and cement fixations do, in fact, have similar rates of revisions and complications and long-term survival.[53,60,61] Likely, improvements in complications and long-term implant survival after cementless fixation can be attributed to advancements in stem design and the increased use of porous ingrowth coating.[62] Few studies have been conducted on the outcomes of press-fit humeral implants in RSA, but short-term to mid-term results suggest that cementless fixation provides outcomes equivalent to those of cemented stems.[63–65] Therefore, due to the easier revision and decreased operative time and cost experienced with press-fit designs, it may be beneficial to use these implants in patients with adequate bone quality (Table 2).

Table 2 Cemented vs Cementless Overview

	Benefits	**Negative**
Cemented	Can be used in patients with poor bone quality, antibiotic carrier	Increased operative time, increased cost, difficult revisions, complications from breakdown of cement over time (eg loosening)
Cementless	Easier revision, decreased operative time, less expensive operation.	Require healthy bone

Influence of Biomechanical Studies

Restoration of the natural anatomy of the shoulder during TSA is crucial for optimizing patient outcomes.[23,66,67] Biomechanical and anatomical studies have significantly contributed to our understanding of the shoulder anatomy and its variation among individuals. These studies motivated the departure from the fixed design of previous implants and the development of prostheses that enabled surgeons to adjust the neck-shaft angle, retroversion, and offset to adapt the prosthesis to the patient's unique anatomy.[23]

The natural humeral head center does not perfectly align with the axis of the humeral shaft. Offset is defined as the distance between the center of the humeral head and the central axis of the canal. Mean medial and posterior offset the native humeral head are reported to be 7 to 9 mm and 2 to 4 mm, respectively.[68] However, individual variation exist. Therefore, prostheses that are modular and allow for the achievement of patient-specific offset are highly beneficial.

The neck shaft angle (NSA) is a crucial measurement in TSA; defined as the angle between a line drawn down the humeral shaft and a line perpendicular to the articular segment's base. The mean NSA is reported as 135 to 140, but previous literature has reported a range from 115 to 150.[69] Prior studies, such as Pearl and Kurutz have demonstrated that prostheses with fixed NSAs are unable to accurately reconstruct the humerus.[70] While fixed NSAs can be used in patients whose NSA that matches that of the prosthesis, those with a NSA mismatch may experience displacement of the humeral head center from its natural position, resulting in loss of motion.[68] Humeral retroversion is defined as the angle between the transepicondylar axis and the articular margin plane.[67] It is also highly variable, ranging from 10 to 55 degrees.[71] Early TSA techniques recommended osteotomy at 30 to 45 degrees of retroversion. However, with increased knowledge of the variability in humeral retroversion, it is recommended to individualize retroversion of the osteotomy to the patient.[72] The ability to vary both NSA and retroversion has been incorporated into more modern prosthetic designs with the goal of optimizing near anatomical reconstruction.[68]

Similar considerations have been applied in the development of RSA prostheses. Grammont's initial design distalized and medialized the center of rotation and had a NSA of 155.[39,73] This design aimed to reduce shear forces at the glenoid bone-implant interface while increasing deltoid tension. However, clinical outcomes using this implant system demonstrated that medialization of the humerus impaired internal and external rotation. Furthermore, in combination with an NSA of 155, it resulted in impingement along the scapular neck, leading to scapular notching.[73] Previous studies have demonstrated that decreasing NSA leads to an increase in range of motion, thereby decreasing the risk of scapular notching.[74–76] Therefore, more modern implants with NSAs of 135 to 145 degrees have been employed to avoid these complications. Grammont's original design also relied on a polyethylene inlay system. In a prospective review of RSA designs in patients with cuff tear arthropathy Frislederer et al noted improved rotation in lateralized RSA designs as compared to the traditional Grammont design. Additionally, Frislederer found that patients experienced improved shoulder flexion and abduction in lateralized and distalized RSA designs.[77] Studies have suggested even better outcomes with use of onlay and curve-stem designed implants with varying NSA as compared to inlay systems.[78] The onlay system increases bone preservation, deltoid moment arm, and tension of rotator cuff muscles, leading to improved outcomes. However, they are associated with an increased risk of acromial fractures.[39,78] A prospective review completed by Freislederer et al it was noted that in patients with cuff tear arthropathy, lateralized and distalized RSA resulted in improved shoulder flexion and abduction along with decreasing scapular notching.[77]

Implant Materials

Traditionally, TSA implants are composed of titanium (Ti) or cobalt-chromium-molybdenum (CoCrMo) alloys.[79] The first prosthesis created by Neer was composed of CoCrMo, also known as vitallium.[3] CoCrMo is reported to be stronger than Ti, making it less susceptible to wear and damage and more suitable for articulating components of the shoulder implant. However, Ti offers better osteointegration and osteoconduction benefits, making it an ideal component for the humeral stem.[79] Polyethylene is a common bearing material used in TSA due to is durability, but, over time, it can experience wear, potentially leading to implant loosening. Treatments like cross-linking and vitamin E have been implemented with newer implants to reduce wear rates of polyethylene components.[78,79] Recently, pyrolytic carbon has been utilized as an implant material for hemiarthroplasties of the shoulder. Theoretically, it reduces glenoid wear by regenerating fibrocartilage and encouraging bone repair. Preliminary studies indicate improved functional outcomes and range of motion with this implant material.[80] Long-term evaluations are still necessary to conclude if this material is superior to traditional metallic implants.

Glenoid Component

Fixation and Design

The fixation and design of the glenoid component in Total Shoulder Arthroplasty (TSA) are pivotal aspects influencing the overall success of the procedure. The glenoid component replaces the damaged or degenerated glenoid socket, and its secure fixation is essential for the stability and functionality of the shoulder joint. Contemporary advancements in TSA have witnessed the development of diverse glenoid component models, including cemented polyethylene, uncemented metal-backed, and hybrid implants. These designs prioritize bone integrity and aim to closely replicate the natural anatomy of the shoulder. The fixation methods may involve cementation or press-fit techniques, with an emphasis on achieving stability and minimizing the risk of component loosening or dislocation. Additionally, the glenoid component design considers factors such as implant longevity, range of motion, and joint biomechanics to optimize postoperative outcomes. Innovations in glenoid component fixation and design contribute significantly to the effectiveness of TSA, addressing complex shoulder pathologies, enhancing surgical precision, and ultimately improving patient satisfaction.

Conforming vs Non-Conforming

The first glenoid component design introduced by Neer was a conforming, keeled and cemented all-polyethylene (all-PE) design. A conforming design refers to an equal diameter of curvature between the humeral and glenoid implant articulating surfaces, while a non-conforming design refers to a mismatch in the diameter of curvature between the two surfaces.[81] Advantages of a conforming design include greater distribution of surface contact and increased stability.[82,83] However, in a native shoulder, translation occurs between the articular surfaces during shoulder motion. These forces are absorbed by the cartilage and labrum. After a replacement, translation still occurs, but the direct contact of the articular surfaces results in loading of the glenoid rim.[83,84] Repetitive stresses applied to the rim of the glenoid can cause the opposite side of the implant to lift and detach from the bone through the rocking horse mechanism, resulting in loosening, a major concern in early glenoid implant designs.[84] To address these concerns, non-conforming implants were introduced. Non-conforming designs allow for increased translation but also increase contact pressures, raising concerns for polyethylene wear and instability.[27,82,85] A consensus on the optimal radial mismatch has not been decided and designs vary greatly. However, a study conducted by Walch et al demonstrated that designs with a radial mismatch greater than 5.5 mm, but less than 10 mm were associated with less radiolucent lines.[83]

Inlay vs Onlay Design

Inlay glenoid implants present a promising approach to avoid the rocking horse mechanism and mitigate risk of glenoid loosening. Previous literature indicates that onlay glenoids have been associated with radiolucent lines in a substantial percentage of cases, ranging from 30 to greater than 75%.[86] Compared to the onlay design, inlay glenoids are implanted within the glenoid fossa and surrounded by native bone. Theoretically, the circumferential bone support offered by this design could counteract the forces generated during translation, thereby resisting loosening.[27,87] Biomechanical studies have demonstrated that inlay designs exhibit better resistance to loosening compared to onlay implants.[86] These findings have been further supported by clinical studies demonstrating that inlay glenoid implants not only improve clinical outcomes but also contribute to a reduction in revision rates and radiographic evidence of loosening.[88,89] Despite the potential advantages of inlay implants over onlay designs, limited options are currently available for use.[87]

Larose et al performed a meta-analysis and Meshram et al conducted a retrospective review highlighting higher ASES scores in the inlay cohorts compared to the onlay cohorts.[90] Contrarily, other studies, including Giordano's, revealed no significant differences in ASES or CMS between these two groups.[91] Range of motion (ROM) comparisons varied across studies, showing discrepancies favoring the inlay or onlay configurations. However, Jackson's systematic review discovered better forward flexion in the onlay group at 142° compared to 136° in the inlay group, although this difference lacked statistical significance.[92] Similarly, in Jackson's study, abduction measurements did not significantly differ at 126° for onlay versus 123° for inlay. However, Jackson did identify a significant difference in ER measuring 39° for onlay and 32° for inlay configurations.[90,92,93] The Visual Analog Scale (VAS) also showed no significant variance between the inlay and onlay groups, measuring 1.42 versus 1.3 respectively.[92] While research surrounding inlay vs Onlay configuration is still inconclusive, it is important to note that in a review of the literature of RSA Franceschi et al reported that a lateralized glenoid with 135° of inlay is the closest to the native shoulder[94] (Table 3).

Table 3 Inlay vs Only Overview

Glenoid Design	Benefits	Negatives
Inlay	Resists loosening, reduced revision rates compared to onlay, anatomically more similar to native shoulder	Limited options available
Onlay	Possibly preserves bone stock better than inlay components, readily available.	Decreased clinical outcomes as compared to inlay components.

Keeled vs Pegged Glenoid Components

Introduced in 1973 as part of Neer's original glenoid component design, the keeled component has seen various iterations, culminating in a tapered "fin" with a rectangular geometry. In contrast, the more recent pegged design incorporates a variable number of pegs of different lengths. Biomechanical studies indicate that pegged fixation exhibits greater resistance to high shear forces, potentially leading to a reduced risk of loosening compared to keeled glenoid components. Importantly, the original glenoid components were keeled.[27,95,96] They demonstrated good survival but a high rate of radiographic loosening.[27,95,96] In response, keeled designs were implanted with less cement and minimal cancellous bone removal to mitigate risk of radiological changes.[27,97] Prior to these advances in surgical technique, pegged glenoid components were introduced to preserve bone, aiming to enhance implant survival and minimize implant migration. Studies have demonstrated that pegged components indeed exhibit lower rates of radiographic loosening and revision.[98,99] However, clinical outcomes are comparable between the two designs[27,95,96] (Table 4).

Shapes

Glenoid component shapes come in two primary forms: anatomic or oval shaped. The anatomic shape mirrors the native glenoid and is described as "pear-shaped". There is limited literature demonstrating the superiority of one shape over the other, however it is generally accepted that surgeon preference dictates the necessity to select a shape that fills the glenoid surface without excessive overhang.[82,87,100]

Augmented Glenoid Components

Glenohumeral osteoarthritis is associated with abnormal version of the glenoid surface. Typically, arthritic changes result in a retroverted glenoid, compromising its stability. The traditional approach for correcting retroversion during TSA has been eccentric reaming. However, this technique requires substantial bone removal, prompting the exploration of alternative methods.[101] Augmented glenoid components, essentially asymmetric glenoids, have been introduced as a potential solution to avoid excessive reaming and bone loss. Rice et al investigated the use of an augmented glenoid component in patients with severe posterior glenoid wear.[102] They concluded that these components achieved satisfactory outcomes, including excellent results in 36% of patients and satisfactory results in 50% of patients according to a modified Neer result rating system; however, the advantage over other designs was considered marginal, leading to discontinuation of its use. Recently, there has been a renewed interest in these implants for correcting retroversion. Short-term evaluations suggest that these implants are a reliable option for treating patients with significant posterior glenoid

Table 4 Comparison Between Keeled and Pegged Components

Glenoid Component Type	Design	Benefits	Negatives
Keeled	Tapered fin with rectangular geometry	Good survival rates	High rate of radiographic loosening
Pegged	Variable pegs with different lengths	Greater resistance to high shear forces, reduces risk of loosening, lower rates of loosening along with lower revision rates	

wear and demonstrate comparable results to standard designs.[103,104] Assessments of augmented glenoid components highlighted improvements in ROM. In Sheath's study, patients with full wedge posterior augmented glenoid demonstrated a mean postoperative FE of 151°, abduction of 138°, and ER at 51° at the 2-year follow-up.[103] However, additional studies need to be done to evaluate long-term outcomes.

Central Screw vs Post

Glenoid component loosening also poses a concern for RSA, specifically glenoid baseplate loosening. In Grammont's initial design, the baseplate had a central post and peripheral screw fixation. Since then, various baseplate designs have been developed to maximize stability, one of the primary elements being a central stabilizing fixation. This central fixation is generally a post, a Monoblock screw baseplate, or a modular screw.[105] Bercik et al reported that both options demonstrate good outcomes, with mean change in ASES from pre-operative to post-operative of 40.0 ± 24.2 with a central screw compared to 41.6 ± 20.8 with a central post ($p = 0.617$). Additionally, there was no significant difference in revision rates (0.8% central screw, 2.3% central post; $p = 0.22$) or loosening rates between the designs.[106] Therefore, the choice of fixation type is likely to depend on surgeon preference and the most suitable option for the patient's specific anatomy.

Implant Materials

The original glenoid implant was designed with all-polyethylene (all-PE) material. In an attempt to improve glenoid fixation, newer designs, such as metal-backed and hybrid components have been explored. Zimmer's first-generation trabecular metal glenoid component, designed to promote bony ingrowth, was introduced in 2003. Budge et al performed an investigation of this design on 19 shoulders. They found that patients had improvement in pain (8.6 to 2.9, $P<0.0001$), forward elevation (75 to 131, $P<0.0001$), and mean ASES score (21 to 70, $P<0.05$); however, 4 implants (21%) failed secondary to a fracture at the keel-glenoid surface. This design was abandoned in 2005, due to additional reports of glenoid component failure secondary to fracture at the keel-glenoid interface.[94,107] The design underwent revision, and a second-generation component was introduced in 2009. Favorable outcomes were noted by Merolla et al[94] including significant increases in from pre-operative to post-operative CMS (23.2 to 69.8; $P <0.001$) and pre-operative to post-operative ASES (24.1 to 93.4; $P= 0.009$) however, subsequent studies continued to report inadequate results with this design, including metallic debris formation, and osteolysis.[108–110] In a review of metal-backed glenoid and all-PE components, all-PE components exhibited higher rates of radiolucent lines and loosening. However, the revision rate for metal-backed components was more than three times that of all-PE.[111] As metal-backed glenoid failed to address concerns of failure and loosening, hybrid designs were introduced. Hybrid designs aim to combine the long-term benefits of bony ingrowth in metal-backed components with the initial stability of all-PE components. These designs typical consist of peripheral polyethylene pegs and a metal post or cage. Evaluation of this design have been positive results, with studies indicating that hybrid glenoid components result in good clinical outcomes.[112,113] However, long-term evaluations will need to be conducted to evaluate for superiority over one component type or the other (Table 5).

Table 5 Implant Materials Comparison

Implant Material	Benefits	Negatives
First generation trabecular metal glenoid component	Promotes bony overgrowth	Glenoid failure secondary to fracture at the keel-glenoid surface.
Second generation trabecular metal glenoid component	Results in improved patient reported outcomes compared to first generational components	Lower rates of glenoid failure compared to first generation.
Polyethylene components	Lower revision rates than metal components, provide good initial stability.	Higher rates of radiolucent lines and loosening as compared to metal components
Hybrid designs	Promote bony in growth, and has good initial stability. Overall positive clinical outcome scores.	Long term effects still need to be further studies.

Discussion

Outcome Measures and Results of Clinical Studies

Complications and Solutions

Understanding the complications associated with new implant systems is crucial for comprehending superior systems and enhancing patient outcomes. Bohsali et al found that shoulder arthroplasty commonly presents with complications such as instability, periprosthetic fractures, infection, loosening, and nerve injury.[114] Among recent implant systems, instability has emerged as a primary concern.[78] To address this, long-stemmed RSA was designed to mitigate instability through lateralization which improves deltoid tension without the need for additional humeral lengthening.[115] Traditional stemmed implants present complications like humeral component loosening and periprosthetic fractures.[114] Conversely, stemless components show the potential to reduce fracture risk and operative time while maintaining comparable efficacy to stemmed implants.[48,116–118] Complications in the stemless approach, as observed by Krukenberg, include a 6.7% total complication rate, including intraoperative fractures and temporary nerve palsies.[45] Kostretzis' systematic review reported a 6.5% total complication rate in stemless RSA, with 3.3% related to humeral components.[119] Scapular notching occurred in 15.2%, and radiographic lucencies were present in 0.8% of cases, with 1.9% intraoperative and 4.6% postoperative complications. Reoperations mainly occurred due to instability (1.7%), while postoperative VAS pain was reported at 2.[119] A comparative study by Uschok et al which compared stemless and stemmed implants revealed similar functional outcomes at the 5-year mark, but the stemless group reported one case of glenoid loosening.[50] Huguet et al reported seven complications among 70 patients using stemless implants, primarily intraoperative cracks which all resolved uneventfully within two months.[120] Gallacher's study on stemless TSA components displayed a 5% overall reoperation rate, with 4% for prosthetic revisions. Rotator cuff failures occurred in eight shoulders, necessitating four revisions.[46] Smith's prospective review noted a low revision rate of 1.3%.[47] Stemless implants may show superiority in complications due to a lower risk of perioperative fractures while maintaining similar functional outcomes, but further investigation is required to enhance their effectiveness.

Comparative data between inlay and onlay configurations in RSA remain scarce. In Meshram's retrospective series, the onlay configuration displayed a slightly higher complication rate (15%) than the inlay (13%), though this disparity lacked statistical significance.[90] Larose's meta-analysis underscored distinctions in scapular notching (28.9% for inlay vs 16.9% for onlay) and spine fractures (3.6% for inlay vs 3.8% for onlay) between the two groups, indicating the need for further investigation.[93] Giordano's study noted one dislocation in the glenoid component and one overall dislocation in the onlay group.[91] Conversely, the inlay group reported one patient with an infection and one dislocation requiring surgery; however, these differences did not achieve statistical significance.[91] Jackson's findings revealed a higher incidence of scapular fractures in the onlay group at 1.94% compared to 0.66% in the inlay group, but this disparity was not statistically significant. Similarly, acromial fractures did not show significant differences.[92] However, a significant finding emerged: the inlay humeral component exhibited higher scapular notching than the onlay configuration (23.2% vs 7.7%).[92] Comparative data between inlay and onlay configuration display differences in complications that make it difficult to determine which configuration is superior, and as shown previously functional outcomes are also similar. Due to this it is difficult to determine which configuration is better, and further research is needed.

In a retrospective analysis evaluating convertible stems, fewer complications were observed in retained stems than exchanged stems for reverse RSA (0% vs 15%).[51] With the retained stem group also displaying better PROs, it seems logical that convertible stems are a viable option in patients. However, the research in this field remains limited and is subject to further evaluation.

Augmented glenoid components exhibit a 2.6% complication rate and a 1.9% revision rate, involving dislocations, prosthetic joint infections (PJI), glenoid loosening, and nerve injuries.[78,121] Long-term data for augmented glenoid components remains limited, with short-term studies indicating promising revision rates of 5% in the 2–3-year follow-up but necessitating further assessment.[78] The degree of augmentation angle seems critical. Priddy found that posteriorly augmented glenoid components had similar improvements to ROM and PROs. However, the 16-degree wedge had a high failure rate, and the authors of that study recommended no longer using the 16-degree wedge in their practice.[103]

Further Directions

The rates of primary and revision shoulder arthroplasty in the United States and globally continue to grow; RSA is experiencing the most rapid growth and is projected to triple in the next two decades as indications for RSA broaden.[122–124] This increase raises concerns about the availability of resources and trained surgeons to manage these procedures domestically and internationally.[122] Thus, it becomes imperative to identify optimal implants that effectively treat patients and reduce the necessity for revision surgeries. The landscape of implants is experiencing significant expansion, with numerous new designs and innovations entering the market annually. Notably, there is a growing trend towards stemless implants.[78,125] These designs aim to achieve 3-D reconstructions of the humeral head by establishing the humeral center of rotation independently from the shaft access.[126] Marigi et al outlined the benefits of stemless implants, including reduced operative time, better preservation of bone stock, and easier revisions.[125] Additionally, augmented glenoid components are gaining attention for potentially reducing bone removal and shear stress.[78]

While the early days of arthroplasty involved ivory devices implanted by Gluck in the 1880s, contemporary devices predominantly use metal and polyethylene.[2,127] An exciting innovation in shoulder arthroplasty involves the use of ceramic heads. Although ceramic heads lack FDA approval, studies suggest their potential to reduce polyethylene wear rate in arthroplasty devices when used with ceramic humeral heads.[98,128] Other materials under exploration include vitamin E, which is recognized for its antioxidant properties and potential to enhance the longevity of polyethylene by protecting it against oxidation.[79,129] Another intriguing material is pyrolytic carbon, which has shown good biocompatibility and has been utilized in various medical applications.[130] While past investigations have shown promise in upper extremity surgeries, its use in shoulder arthroplasty is still being explored, particularly with the current focus on HA and pyrolytic carbon.[131,132] Pyrolytic carbon in HA has exhibited positive clinical outcomes in pain and function in the glenohumeral joint.[133]

As shoulder arthroplasty evolves, we must consider our approaches to the procedure. The choice of approach for RSA predominantly revolves around anterosuperior and deltopectoral methods, yet determining which approach provides superior outcomes remains to be determined.[134] Seok et al suggested that since outcomes are similar between the two, surgeons should opt for the approach they are most familiar with.[135] As implants evolve and new technologies enter the realm of shoulder arthroplasty, this aspect requires further evaluation.

Previously, shoulder arthroplasty relied on 2-D imaging for pre-operative planning, but it has transitioned to 3-D planning, which has changed the understanding of glenoid anatomy in specific patients.[136] This advancement has resulted in surgeons selecting the correct augmented glenoid component more accurately than traditional 2-D planning.[136] Furthermore, emerging technologies like mixed-reality holograms and augmented reality show promise for pre-operative planning. Abdic et al found that initial studies suggest no significant differences in procedural time or guide pin positioning compared to traditional software planning.[137] However, the integration of such systems may involve a learning curve. As mixed reality becomes more prevalent, it is anticipated that pre-operative planning will be enhanced, and surgical durations will be reduced while catering to patient-specific anatomy.

Artificial intelligence (AI) is a developing concept within shoulder arthroplasty that represents a source of potential excitement.[138] Current studies on AI primarily focus on image analysis, pre-operative complication risk prediction models, and patient satisfaction.[139] Recent research has explored using AI to predict patients' postoperative internal rotation after shoulder arthroplasty.[140] The potential to predict patient outcomes based on different implant effects by using AI presents an intriguing avenue for future exploration. Additionally, AI is being used to determine postoperative discharge locations.[141,142] As the number of shoulder arthroplasty procedures grows, AI holds promise for predicting patient outcomes based on implant types to streamline healthcare and discharge processes. The future of AI in shoulder arthroplasty and implant development appears boundless, with promising improvements in patient outcomes and operational efficiency within the orthopedic community.

Conclusions

In conclusion, this comprehensive review highlights significant advancements and innovations in shoulder arthroplasty, providing valuable insights into various implant systems and their outcomes. The investigative analysis of stemless

implants, augmented glenoid components, convertible stems, and inlay vs onlay configurations has demonstrated improvements in patient-reported outcomes, range of motion, and overall success rates. The comparative analysis between different configurations and components underscores the need for ongoing research to discern optimal choices for specific patient profiles. Overall, recent innovations have shown promising results in reducing complications, enhancing surgical techniques, and improving patient outcomes. The booming field of artificial intelligence (AI) and the potential integration of robotics into shoulder arthroplasty present exciting possibilities for personalized implant development and precision in surgical procedures.

These advancements, coupled with the evolving regulatory landscape, also call for continued research to address complications, refine implant designs, and establish international standards for safety and efficacy. While acknowledging the exponentially increasing volume in shoulder arthroplasty cases, it is essential to ensure that the rapid growth aligns with patient-centered care and ethical considerations. Surgeons must remain vigilant in understanding the regulatory processes, research and developmental pipelines, and selecting implants with informed consent. As the landscape of shoulder arthroplasty continues to evolve, ongoing research and collaboration are paramount to optimizing patient outcomes, refining surgical practices, and ensuring the longevity and effectiveness of innovative implant systems.

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